Ecol Res (2014) 29: 433–439
DOI 10.1007/s11284-014-1135-4

ORIGINAL ARTICLE

Baoming Du · Hongzhang Kang · Jukka Pumpanen
Penghua Zhu · Shan Yin · Qin Zou · Zhe Wang
Fanqian Kong · Chunjiang Liu

Soil organic carbon stock and chemical composition along an altitude gradient in the Lushan Mountain, subtropical China

Received: 26 June 2013 / Accepted: 18 February 2014

Abstract Soil organic carbon (SOC) stock in mountain ecosystems is highly heterogeneous because of differences in soil, climate, and vegetation with elevation. Little is known about the spatial distribution and chemical composition of SOC along altitude gradients in subtropical mountain regions, and the controlling factors remain unclear. In this study, we investigated the changes in SOC stock and chemical composition along an elevation gradient (219, 405, 780, and 1268 m a.s.l.) on Lushan Mountain, subtropical China. The results suggested that SOC stocks were significantly higher at high altitude sites (1268 m) than at low altitude ones (219, 405, and 780 m), but the lower altitude sites did not differ significantly. SOC stocks correlated positively with mean annual precipitation but negatively with mean annual temperature and litter C/N ratio. The variations in SOC stocks were related mainly to decreasing temperature and increasing precipitation with altitude, which resulted in decreased litter decomposition at high altitude sites. This effect was also demonstrated by the chemical composition of SOC, which showed lower alkyl C and higher O-alkyl C contents at high altitude sites. These results will improve the understanding of soil C dynamics and enhance predictions of the responses of mountain ecosystem to global warming under climate change.

Keywords Soil organic carbon · Chemical composition · Vegetation type · Mountain ecosystem · Subtropical China

Introduction

The global soil organic carbon (SOC) pool is estimated to be 2500 gigatons, close to 3.3 times the size of the atmospheric pool and 4.5 times that of the biotic pool (Lal 2004). Thus, small fluctuations in SOC may influence ecosystem sustainability, global carbon budgets, and atmospheric CO_2 concentrations (Amundson 2001). Mountain forest ecosystems store approximately 26 % of terrestrial carbon (Garten and Hanson 2006) and play an important role in the global carbon cycle (Gower 2003). Recently, there has been a strong interest in mountain soils because montane ecosystems are be vulnerable to climate change (Beniston 2003; Djukic et al. 2010; Britton et al. 2011) and are useful “ecological indicators” (Podwojewski et al. 2011). Mountain ecosystems in the context of climate change have been extensively researched (Rodeghiero and Cescatti 2005; Tewksbury and Van Miegroet 2007; Leifeld et al. 2009; Bu et al. 2012).

Changes in climatic variables, i.e., precipitation and temperature, along altitudinal gradients in mountain forest ecosystems influence the type of vegetation and, consequently, the amount, chemical composition, and turnover of SOC (Jobbágy and Jackson 2000; Lemenih and Itanna 2004). Therefore, SOC stocks change with

Electronic supplementary material The online version of this article (doi:10.1007/s11284-014-1135-4) contains supplementary material, which is available to authorized users.

B. Du · H. Kang · P. Zhu · S. Yin · C. Liu (✉)
School of Agriculture and Biology and Research Centre
for Low-Carbon Agriculture, Shanghai Jiao Tong University,
Dongchuan Rd. 800, Shanghai 200240, People’s Republic of China
E-mail: chjliu@sjtu.edu.cn
Tel.: +86-21-34206603
Fax: +86-21-34206603

H. Kang · P. Zhu · S. Yin · C. Liu
Key Laboratory of Urban Agriculture (South),
Ministry of Agriculture, Dongchuan Rd. 800,
Shanghai 200240, People’s Republic of China

J. Pumpanen
Department of Forest Sciences, University of Helsinki,
P.O. Box 27, 00014 Helsinki, Finland

Z. Wang
Shanghai Forestry Station, Hutai Rd. 1053,
Shanghai 200072, People’s Republic of China

Q. Zou · F. Kong
Nature Reserve of Lushan Jiangxi, Henan Rd. 600,
Jiujiang 332900, People’s Republic of China

elevation (Garten and Hanson 2006) as precipitation increases and temperatures decrease (Hontoria et al. 1999; Lemenih and Itanna 2004; Wang et al. 2004). However, studies of soil C stocks in alpine regions revealed different relationships with altitude, including a decrease, unimodal response, or lack of change (Britton et al. 2011). For instance, Djukic et al. (2010) reported that SOC stocks increased with elevation at low altitudes but decreased with elevation at high altitudes in the Northern Limestone Alps of Austria. In the Swiss Alps, Leifeld et al. (2009) suggested that soil C stocks were not related to elevation. Thus, to understand SOC dynamics in alpine ecosystems, the characteristics of SOC in different climate zones should be investigated.

Recently, solid-state ^{13}C cross-polarization magic angle spinning nuclear magnetic resonance (CP/MAS-NMR) spectroscopy has become an important tool for examining the chemical structures of natural organic materials and the chemical changes during decomposition (Baldock et al. 1997). Baldock et al. (1992) proposed that these chemical changes can be grouped into three stages (i.e., loss of O-alkyl carbon, decomposition of aromatic carbon, and accumulating alkyl carbon). Numerous studies have demonstrated that the decomposition of organic material is usually associated with increasing alkyl C and decreasing O-alkyl C concentrations (Baldock et al. 1997; Zech et al. 1997; Zimmermann et al. 2012). Moreover, alkyl C/O–alkyl C (García and Faz 2012) and aromatic C contents (Huang et al. 2008) are good indicators of the extent of organic matter decomposition in forest soils. However, few works have used ^{13}C CP/MAS-NMR spectroscopy to study the chemical composition of SOC in subtropical China (Wang et al. 2010, 2013a), and even fewer have examined the chemical composition of SOC along an elevation gradient.

Lushan Mountain is located in the middle-lower plain of the Yangtze River in central subtropical China, with altitudes from 30–1470 m a.s.l.(Liu and Wang 2010). As elevation increases, an opposite trend of heat and water (OHW) occurs, i.e., temperature decreases 7 °C and precipitation increases by approximately 900 mm from low to high altitudes, a typical mountain climate in subtropical China. The corresponding change in vegetation is from evergreen broadleaf forests in the foothills to deciduous forests at the summit. Previous studies have examined variations in SOC stocks with climate (Tewksbury and Van Miegroet 2007; Podwojewski et al. 2011), soil properties (Torn et al. 1997; Groenigen et al. 2006), and vegetation types (Lemenih and Itanna 2004; Bu et al. 2012). For instance, decreasing temperatures with increasing altitudes in the Sierra Nevada of California have been shown to limit SOC turnover, resulting in enhanced SOC accumulation at higher elevations (Trumbore et al. 1996). In this study, we studied Lushan Mountain to test the hypothesis that SOC stocks increase with altitude, mainly as a result of climate differences. We investigated SOC stocks and their chemical composition along the elevation gradient of Lushan Mountain and examined the effects of temperature, precipitation, and litter quality on SOC stocks.

Materials and methods

Study area

The study area is located in the Lushan Nature Reserve (29°31′–29°41′N, 115°51′–116°07′E), south of Jiujiang City, Jiangxi Province, China (Fig. S1). The area has a subtropical monsoon climate. The mean annual precipitation (MAP) ranges from 1308 to 2068 mm, and the mean annual temperature (MAT) from 17.1 to 11.6 °C (Liu and Wang 2010).

Lushan is an isolated mountain body situated in the center of the vast plain of the middle and lower reaches of the Yangtze River. The mountain covers an area of about 300 km^2 along an altitude range from 30 to 1474 m. Soil types on Lushan Mountain change from ferric alisols at low elevations to haplic alisols at high ones (Liu and Wang 2010), according to the FAO soil texture classification. At low altitudes (50–600 m) are evergreen forests dominated by several Fagaceae tree species, including *Castanopsis sclerophylla*, *Castanopsis eyrei*, and *Lithocarpus glaber*, and some evergreen woodland species and shrubs. Deciduous trees grow at middle altitudes (600–1000 m), where some *Cryptomeria japonica* plantations were also established about 50 years ago (Liu and Wang 2010). *Lindera obtusiloba* forest, consisting of *Cerasus serrulata*, *Castanea seguinii*, *Tilia breviradiata*, and a few shrubs, occurs at about 1200 m a.s.l. (Table S1).

Sampling of soil and litter

Two study sites were established at 219 and 405 m (low altitudes), one at 780 m (middle), and one at 1268 m (high). At each site, three sampling plots (each 20 × 20 m) were delineated randomly. Five litter samples (50 × 50 cm) were randomly collected in each plot. After removal of the litter layer, soil samples were collected at 0–10, 10–20, 20–30, 30–40, 40–50, and 50–60 cm depths. A total of five soil cores were randomly collected using a 2-cm-diameter stainless-steel earth borer in each plot and bulked to make a composite sample for each depth interval. In addition, one soil profile was excavated in each plot. Soil samples of fixed volume were taken from each soil layer, where possible, to determine soil bulk density. This work was conducted based on Forestry Standards “Observation Methodology for Long-term Forest Ecosystem Research” of People’s Republic of China.

Soil samples were air-dried, gently ground, passed through a 2-mm sieve to remove coarse living roots and gravel, and then ground with a mill to pass through a 0.149-mm mesh sieve before chemical analyses. Litter samples were oven dried (65 °C) and ground to a fine powder with a Tecator sample mill (Subang, Shanghai, China) prior to chemical analyses.

Chemical analyses

Soil pH was measured in H_2O with a soil-to-solution ratio of 1:5 (Porter and Robson 1987). The total organic carbon and nitrogen content of soil, litter, and vegetation were determined with Vario EL III element analyzer (Elementar, Hanau, Germany). The SOC concentrations of soil samples from different depths were measured using the dichromate oxidation method (Kalembasa and Jenkinson 1973).

The chemical compositions of C in litter and soil layers at 0–10, 30–40, and 50–60 cm depths were analyzed with solid-state ^{13}C CP/MAS-NMR. The litter samples were dried to constant weight at 65 °C and ground in a Wiley mill. The soil samples were pretreated with 10 % (v/v) hydrofluoric acid (HF) before the NMR spectroscopy (Wang et al. 2010) to reduce Fe^{3+} and Mn^{2+} (Schmidt et al. 1997) and concentrate organic C for a more accurate signal-to-noise ratio (Wang et al. 2010). About 10 g of the ground sample was shaken with 50 mL HF for 2 h. After centrifugation (1300*g*) for 10 min, the supernatant was removed. The procedure was repeated five times. The remaining sediment was washed five times with 50 mL deionized water to remove residual HF before freeze drying.

The solid-state ^{13}C CP/MAS-NMR spectra of litter and soil samples were obtained at a frequency of 100.64 MHz using a Bruker AVANCE-III 400 MHz NMR spectrometer (Bruker Biospin, Rheinstetten, Germany) operated at 75.42 MHz for ^{13}C. The contact time was 1.5 ms with a 1 s recycle delay, and the magnetic angle spinning rate was 5 kHz (Wang et al. 2010). About 12,000 scans were collected for soil samples and 10,000 scans for litter samples (Jien et al. 2011). The chemical shift regions 0–45, 45–110, 110–160, and 160–220 ppm were assigned to alkyl C, O-alkyl C, aromatic C, and carboxylic C, respectively (Rumpel et al. 2002; Wang et al. 2010). The sources of organic carbon were alkyl C derived from lipids, fatty acids and plant aliphatic polymers; O-alkyl C primarily from cellulose and hemicelluloses, as well as starch, proteins, and carbohydrates; aromatic C from lignin and tannins; and carboxyl C from lipids, aliphatic esters, and amide carboxyls (Baldock et al. 1997; García and Faz 2012). The signal intensities in the respective chemical-shift regions were expressed as a percentage of the area of the total spectra. The relative contents of different chemical structures were therefore calculated (Jien et al. 2011).

Statistical analyses

One-way ANOVA was used to evaluate the differences among SOC stocks by altitude. Linear regressions were performed to correlate MAT, MAP, and litter C/N ratio with SOC stocks. All analyses were performed with SPSS 16.0 (IBM, Chicago, IL, USA) and SAS (SAS Institute Inc., Cary, NC, USA) software.

Results

SOC spatial distribution

The amount of total SOC in the upper 60 cm of soil increased with altitude from 7.60 kg m^{-2} at 405 m a.s.l. to 15.14 kg m^{-2} at 1268 m a.s.l. (Fig. 1b). SOC stocks were significantly higher at 1268 m a.s.l. than at lower altitudes (219, 405, and 780 m) ($P < 0.05$), but the differences among lower altitudes were not significant (Fig. 1b). At each altitude, SOC stocks generally decreased with soil depth. The surface layer (0–20 cm) contained 52.3, 54.8, 54.6, and 48.9 % of the total C measured in the soil depth of 0–60 cm at 219, 405, 780, and 1268 m a.s.l., respectively (Fig. 1a).

Effects of climate and litter quality on SOC stocks

On Lushan Mountain, temperature decreased with increasing altitude, whereas precipitation increased (Table 1). As a result, SOC stocks were negatively correlated to MAT ($r^2 = 0.89$, $P < 0.0001$) (Fig. 2b) and positively to MAP ($r^2 = 0.89$, $P < 0.0001$) (Fig. 2c). Litter C/N ratio decreased with altitude (Table 2) and was therefore negatively correlated to SOC stocks ($r^2 = 0.67$, $P < 0.01$) (Fig. 2a).

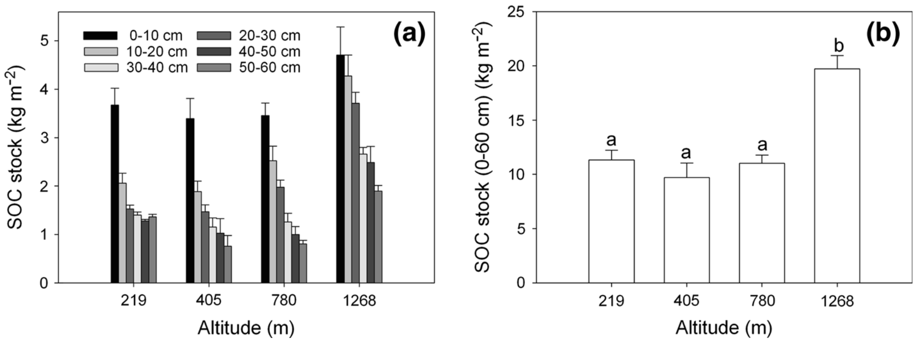

Fig. 1 Soil organic carbon (SOC) stocks at different soil depths and altitudes (**a**) and total SOC stock (0–60 cm depth) at different altitudes (**b**) on Lushan Mountain, China. *Error bars* indicate standard error ($n = 3$). *Different letters* indicate significance at $p < 0.05$

SOC chemical composition

The solid-state ^{13}C CP/MAS-NMR spectra of litter and soils at 219, 405, 780, and 1268 m a.s.l. are shown in Fig. 3. The spectra shared similar patterns but differed in the relative intensity of the different chemical shift regions. The surface soil (0–10 cm) alkyl C decreased from 40.2 % at 219 m to 31.8 % at 1268 m, whereas the O-alkyl C contents varied by altitude, reaching a maximum value of 45.0 % at 1268 m. The aromatic C content increased with altitude, but carbonyl C contents did not change significantly along the altitudinal gradient (Table 3). At each altitude, however, the contents of O-alkyl and aromatic C were lower (except for aromatic C at 1268 m) and those of alkyl and carbonyl C were higher in the topsoil than in the litter.

Discussion

The soil SOC stocks in the upper 60 cm ranged from 7.60 kg m^{-2} at 405 m a.s.l. to 15.14 kg m^{-2} at 1268 m a.s.l. (Fig. 1), consistent with the previous findings by Du et al. (2011) in the same area. The results were within the range of estimates by Lugo et al. (1986) for the 0–17-cm soil layer in a wet subtropical forest of Puerto Rico (7.5 kg m^{-2}), and by Bu et al. (2012) for the 0–30-cm soil layer on Wuyi Mountain (8.27 kg m^{-2}), near Lushan Mountain.

The present study indicated that SOC stocks increased with altitude on Lushan Mountain (Fig. 1b), reflecting a changing balance of soil C inputs and losses (Garten and Hanson 2006). The deceasing tree biomass with altitude indicated (Table S1) that soil C inputs declined along the altitudinal gradient. The results were comparable to those of similar studies carried out at Wuyi Mountain and Shennongjia Mountain (near Lushan Mountain), where both annual net primary production and litterfall inputs declined with increasing altitudes (Bu et al. 2012; Liu et al. 2012). Other than soil C inputs, differences in organic matter decomposition can also result from altitudinal variations in forest soil C stocks and turnover driven by elevation gradients of environmental factors (Garten and Hanson 2006). In this study, the SOC stocks were positively correlated to MAP (Fig. 2c) and negatively to MAT (Fig. 2b), consistent with the negative impacts of low temperature and high precipitation at high altitudes on decomposition and turnover rates of soil organic matter (Bu et al. 2012).

The changes in climatic factors along altitude gradients affect not only decomposition and SOC turnover but also plant community composition in mountain ecosystems (Garten et al. 2000). On Lushan Mountain, vegetation type varies from evergreen broadleaf forests (219 and 405 m), to evergreen mixed forest (780 m), and to deciduous broadleaf forest (1268 m) (Table 1). These vegetation changes result in different litter types and qualities (Wang et al. 2013b) that can be evaluated by

Table 1 Features of climate, vegetation, and soils at different altitudes on Lushan Mountain of subtropical China

Altitude (m)	Site codes (location)	Coordinates	Slope (°)	MAT[a] (°C)	MAP[b] (mm)	Forest types[c]	Soil types
219	A (Tongyuan)	N29°30′39.62″ E115°53′29.42″	33	16.2	1429	EBF	Ferricalisols
405	B (Saiyang)	N29°31′06.67″ E115°54′18.80″	40	15.3	1549	EBF	Alumi-ferricalisols
780	C (Beiyun)	N29°32′33.95″ E115°55′48.20″	38	13.6	1794	EBMF	Haplicalisols
1268	D (Yangtianping)	N29°31′55.35″ E115°56′58.15″	40	11.3	2112	DBF	Haplicalisols

MAT mean annual temperature, *MAP* mean annual precipitation. Climatic data for 1971–2000 were obtained from the Lushan Meteorological Bureau, *EBF* evergreen broadleaf forest, *EBMF* evergreen mixed forest, *DBF* deciduous broadleaf forest

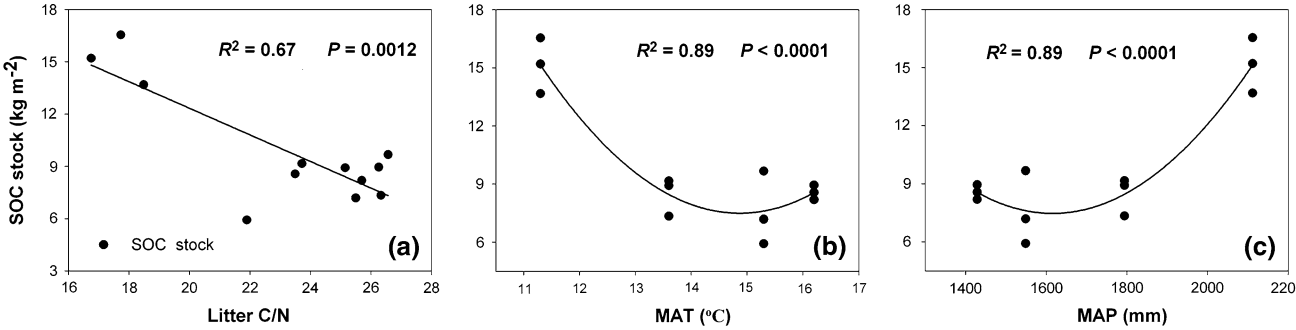

Fig. 2 Relationships between soil organic carbon (SOC) stock (0–60 cm depth) and litter C/N ratio (**a**), mean annual temperature (MAT) (**b**), and mean annual precipitation (MAP) (**c**) on Lushan Mountain, China. The fitted models are: $y = -7.26 + 0.01x$, in the **a**; $y = 140.21 - 17.85x + 0.6x^2$, in the **b**; $y = 88.80 - 0.10x + 0.00003x^2$, in the **c**. C, carbon; N, nitrogen

Table 2 Soil properties at different altitudes on Lushan Mountain

Altitude (m)	Depth (cm)	N (g kg^{-1})	C/N	pH	Soil density (kg m^{-2})	SOC (g kg^{-1})
219	Litter	1.89 ± 0.12	25.15 ± 1.46			
	0–10	2.48 ± 0.35	12.17 ± 1.19	4.29 ± 0.05	1.29 ± 0.07	24.57 ± 0.73
	10–20	1.47 ± 0.14	10.39 ± 0.72	4.30 ± 0.04	1.32 ± 0.05	11.66 ± 0.90
	20–30	1.12 ± 0.13	9.70 ± 0.74	4.32 ± 0.04	1.36 ± 0.07	7.99 ± 0.30
	30–40	1.06 ± 0.13	9.69 ± 1.13	4.37 ± 0.04	1.38 ± 0.07	8.33 ± 0.30
	40–50	0.92 ± 0.03	9.90 ± 0.86	4.42 ± 0.04	1.41 ± 0.06	6.78 ± 0.50
	50–60	0.81 ± 0.06	10.07 ± 0.28	4.47 ± 0.03	1.51 ± 0.02	6.45 ± 0.79
405	Litter	1.79 ± 0.05	24.66 ± 2.45			
	0–10	2.94 ± 0.45	11.81 ± 0.92	4.26 ± 0.23	1.00 ± 0.20	27.53 ± 3.58
	10–20	1.42 ± 0.18	10.93 ± 0.55	4.24 ± 0.18	1.22 ± 0.17	12.59 ± 1.56
	20–30	1.06 ± 0.11	10.45 ± 0.45	4.21 ± 0.32	1.33 ± 0.12	8.58 ± 1.48
	30–40	0.77 ± 0.10	10.51 ± 0.60	4.35 ± 0.16	1.42 ± 0.04	6.51 ± 1.07
	40–50	0.64 ± 0.12	10.15 ± 0.64	4.28 ± 0.12	1.55 ± 0.09	5.22 ± 1.24
	50–60	0.60 ± 0.08	7.76 ± 0.98	4.36 ± 0.11	1.61 ± 0.13	3.91 ± 1.11
780	Litter	1.87 ± 0.06	25.07 ± 1.31			
	0–10	3.29 ± 0.18	13.17 ± 0.78	4.41 ± 0.00	0.80 ± 0.12	34.66 ± 4.14
	10–20	2.11 ± 0.18	16.38 ± 3.61	4.56 ± 0.16	0.96 ± 0.10	20.98 ± 1.62
	20–30	1.46 ± 0.15	13.04 ± 0.43	4.60 ± 0.15	1.05 ± 0.16	15.07 ± 2.12
	30–40	0.90 ± 0.11	12.27 ± 0.92	4.48 ± 0.01	1.17 ± 0.23	9.03 ± 1.81
	40–50	0.71 ± 0.12	11.54 ± 1.15	4.50 ± 0.10	1.24 ± 0.23	6.35 ± 1.57
	50–60	0.66 ± 0.08	9.80 ± 0.59	4.61 ± 0.19	1.30 ± 0.20	4.95 ± 0.96
1268	Litter	2.59 ± 0.21	17.66 ± 0.87			
	0–10	6.08 ± 0.40	12.42 ± 0.30	4.26 ± 0.09	0.63 ± 0.11	68.95 ± 5.02
	10–20	4.28 ± 0.14	13.07 ± 0.24	4.49 ± 0.02	0.76 ± 0.12	47.87 ± 0.88
	20–30	3.13 ± 0.03	12.52 ± 0.32	4.72 ± 0.06	0.95 ± 0.09	29.87 ± 0.45
	30–40	2.29 ± 0.07	11.83 ± 0.59	4.74 ± 0.06	0.99 ± 0.13	20.65 ± 1.33
	40–50	2.05 ± 0.18	11.47 ± 0.92	4.84 ± 0.01	1.10 ± 0.19	17.30 ± 2.79
	50–60	1.76 ± 0.14	9.72 ± 0.29	4.90 ± 0.09	1.23 ± 0.23	12.39 ± 1.38

N nitrogen, *C* carbon, *SOC* soil organic carbon

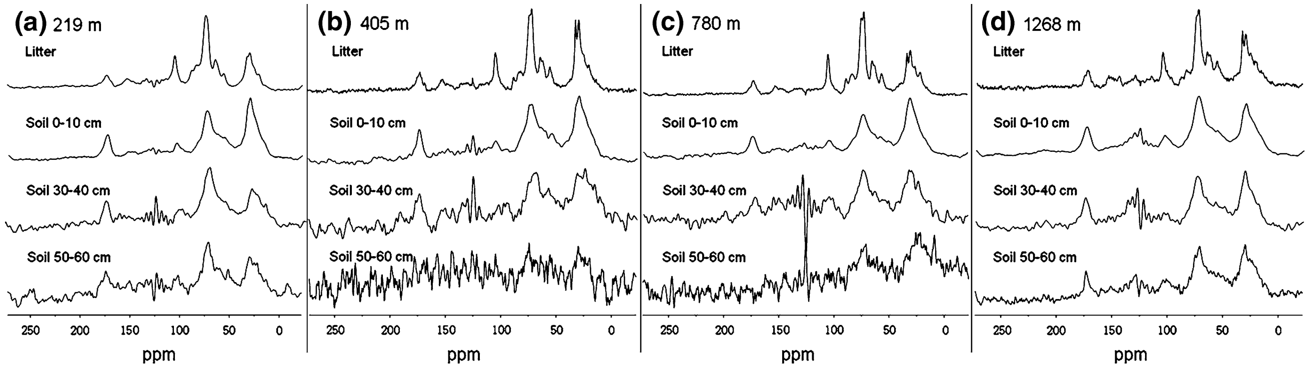

Fig. 3 ^{13}C nuclear magnetic resonance (NMR) spectra obtained from litter and soils (0–10, 30–40, and 50–60 cm depth) at the altitudes of 219 m (**a**), 405 m (**b**), 780 m (**c**), and 1268 m (**d**)

litter C/N ratio (Vesterdal et al. 2008; Wang et al. 2010); a low C/N ratio generally represents good quality litter and a high transfer rate of C from litterfall to mineral soils (Wang et al. 2010). In our results, however, litter C/N ratios decreased with altitude (Table 2) and were negatively correlated to SOC stocks. Other studies have suggested that the chemical changes associated with an increasing decomposition rate are usually characterized by an increase in the functional group alkyl C and a decrease in the group O-alkyl C (Baldock et al. 1997), consistent with our observations that surface soil (0–10 cm) O-alkyl C was high and alkyl C was low at 1268 m a.s.l. compared to lower altitudes. This finding suggests that low C/N ratios in mountain areas do not necessarily result in high transfer rates of C because of low temperatures and high precipitation rates at high altitudes. Hence, we accept our hypothesis that climatic factors are responsible for increasing SOC stocks with altitude because they affect litter decomposition.

According to the results of CP/MAS-NMR spectroscopy, surface soil (0–10 cm) alkyl C decreased with altitude (Table 3), indicating a negative decomposition–elevation relationship on Lushan Mountain due to alkyl C resistance to decomposition (Baldock et al. 1992; Jien

Table 3 Composition of soil organic carbon stocks (%) by different functional groups for litter and soil at different altitudes on Lushan Mountain, China

Altitude (m)	Soil depth (cm)	Functional groups				Alkyl C/O-alkyl C
		Alkyl C	O-alkyl C	Aromatic C	Carbonyl C	
219	LF	23.5	60.6	10.0	6.0	0.39
	0–10	40.2	44.1	6.2	9.4	0.91
	30–40	28.5	49.3	10.3	12.0	0.58
	50–60	25.1	43.5	12.4	15.6	0.65
405	LF	31.6	49.8	10.7	7.9	0.63
	0–10	37.7	43.8	8.1	10.4	0.86
	30–40	33.6	34.3	16.2	15.9	0.98
	50–60	19.0	34.5	25.9	20.6	0.55
780	LF	26.8	58.5	9.2	5.4	0.46
	0–10	41.3	40.5	8.8	9.5	1.02
	30–40	32.1	38.4	17.7	11.8	0.84
	50–60	34.7	35.0	18.3	12.1	0.99
1268	LF	30.7	53.0	10.2	6.0	0.58
	0–10	31.8	45.0	12.8	10.4	0.71
	30–40	31.1	38.6	16.2	14.0	0.81
	50–60	35.2	44.3	11.9	8.7	0.79

LF litterfall

et al. 2011). Similar results were also found by García and Faz (2012) in Peru and by Kavdir et al. (2005) in Turkey. This finding is supported by the surface soil O-alkyl C content being highest at 1268 m a.s.l. (the highest altitude), similar to the observations by Zimmermann et al. (2012) in a tropical forest of Peru, where O-alkyl groups increased from 31 % at 200 m a.s.l. to 59 % at 3030 m a.s.l. O-alkyl C is easily degraded by microorganisms (García and Faz 2012), and a high O-alkyl C content usually indicates un decomposed plant litter (Kavdır et al. 2005). Thus, the variation in SOC chemical composition was in line with the spatial distribution of SOC stock on Lushan Mountain.

At each altitude, SOC stocks decreased with increasing soil depth. This finding, according to the results of CP/MAS-NMR spectroscopy, was due to the facts that more easily decomposed components, such as O-alkyl C, decreased in concentration with soil depth, whereas recalcitrant components, such as aromatic and carboxyl C, increased (Table 3), consistent with the findings by Zech et al. (1989). The decrease in O-alkyl C content can be attributed to the decomposition of more easily metabolized carbohydrates that are mineralized into various microbial products or lost through mineralization to carbon dioxide (Baldock et al. 1992; Preston 1996). Some studies also suggest that humification might enhance the aromatic C content at the expense of O-alkyl C (Quideau et al. 2000; Dalmolin et al. 2006). In this study, the accumulation of aromatic C with soil depth likely indicated an increase in SOC decomposition, as suggested by Jien et al. (2011).

Conclusions

The spatial distribution and chemical composition of SOC stockswere examined across an altitude gradient on Lushan Mountain, subtropical China. Our study suggested that SOC stocks were significantly higher at the high altitude site (1268 m) than at lower altitudes (219, 405, and 780 m), but the differences among the three low-altitude sites were not significant. The changes in SOC stocks were due mainly to the climatic conditions of decreasing temperature and increasing precipitation with altitude, resulting in reduced litter decomposition rates at high altitudes. This conclusion was supported by the SOC chemical composition, which had was lower alkyl C and higher O-alkyl C contents at high altitudes. These results will help scientists to understand soil C dynamics and mountain ecosystems in the context of global climate change.

Acknowledgments We thank Jinhao Qian, Ming Du, Li Zhang, Jingli Hou, Shi Xu, Xianxian Zhang, and Jieli Wu for their assistance with fieldwork and sample analyses and Xiao Sun and Frank Berninger for their comments on earlier drafts of the manuscript. Dr. Rongzhou Man at Ontario Forest Research Institute, Canada, is gratefully acknowledged for his constructive comments and language assistance. We also acknowledge support from the Instrumental Analysis Center of Shanghai Jiao Tong University. This work was supported by the State Key Basic Research and Development Plan of China (2011CB403201) and by the CFERN & GENE award funds for ecological papers.

References

Amundson R (2001) The carbon budget in soils. Annu Rev Earth Planet Sci 29:535–562

Baldock JA, Oades JM, Waters AG, Peng X, Vassallo AM, Wilson MA (1992) Aspects of the chemical structure of soil organic materials as revealed by solid-state ^{13}C NMR spectroscopy. Biogeochemistry 16:1–42

Baldock JA, Oades JM, Nelson PN, Skene TM, Golchin A, Clarke P (1997) Assessing the extent of decomposition of natural organic materials using solid-state ^{13}C NMR spectroscopy. Aust J Soil Res 35:1061–1083

Beniston M (2003) Climatic change in mountain regions: a review of possible impacts. Clim Chang 59:5–31

Britton AJ, Helliwell RC, Lilly A, Dawson L, Fisher JM, Coull M, Ross J (2011) An integrated assessment of ecosystem carbon pools and fluxes across an oceanic alpine toposequence. Plant Soil 345:287–302

Bu X, Ruan H, Wang L, Ma W, Ding J, Yu X (2012) Soil organic matter in density fractions as related to vegetation changes along an altitude gradient in the Wuyi Mountains, southeastern China. Appl Soil Ecol 52:42–47

Dalmolin R, Gonçalves CN, Dick DP, Knicker H, Klamt E, Kögel-Knabner I (2006) Organic matter characteristics and distribution in Ferralsol profiles of a climosequence in southern Brazil. Eur J Soil Sci 57:644–654

Djukic I, Zehetner F, Tatzber M, Gerzabek MH (2010) Soil organic-matter stocks and characteristics along an alpine elevation gradient. J Plant Nut Soil Sci 173:30–38

Du Y, Wu C, Zhou S, Huang L, Han S, Xu X, Ding Y (2011) Forest soil organic carbon density and its distribution characteristics along an altitudinal gradient in Lushan Mountains of China. Chin J Appl Ecol 22:1675–1681

García M, Faz CA (2012) Soil organic matter stocks and quality at high altitude grasslands of Apolobamba, Bolivia. Catena 94:26–35

Garten CT, Hanson PJ (2006) Measured forest soil C stocks and estimated turnover times along an elevation gradient. Geoderma 136:342–352

Garten CT, Cooper LW, Post WM III, Hanson PJ (2000) Climate controls on forest soil C isotope ratios in the southern Appalachian mountains. Ecology 81:1108–1119

Gower ST (2003) Patterns and mechanisms of the forest carbon cycle. Ann Rev Enviro Res 28:169–204

Hontoria C, Rodríguez Murillo JC, Saa A (1999) Relationships between soil organic carbon and site characteristics in peninsular Spain. Soil Sci Soc Am J 63:614–621

Huang Z, Xu Z, Chen C, Boyd S (2008) Changes in soil carbon during the establishment of a hardwood plantation in subtropical Australia. For Ecol Manag 254:46–55

Jien SH, Chen TH, Chiu CY (2011) Effects of afforestation on soil organic matter characteristics under subtropical forests with low elevation. J For Res 16:275–283

Jobbágy EG, Jackson RB (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol Appl 10:423–436

Kalembasa SJ, Jenkinson DS (1973) A comparative study of titrimetric and gravimetric methods for the determination of organic carbon in soil. J Sci Food Agric 24:1085–1094

Kavdır Y, Ekinci H, Yüksel O, Mermut AR (2005) Soil aggregate stability and ^{13}C CP/MAS–NMR assessment of organic matter in soils influenced by forest wildfires in Çanakkale, Turkey. Geoderma 129:219–229

Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627

Leifeld J, Zimmermann M, Fuhrer J, Conen F (2009) Storage and turnover of carbon in grassland soils along an elevation gradient in the Swiss Alps. Glob Change Biol 15:668–679

Lemenih M, Itanna F (2004) Soil carbon stocks and turnovers in various vegetation types and arable lands along an elevation gradient in southern Ethiopia. Geoderma 123:177–188

Liu X, Wang L (2010) Scientific survey and study of biodiversity on the Lushan nature reserve in Jiangxi province. Science Press, Beijing

Liu L, Shen G, Chen F, Luo L, Xie Z, Yu J (2012) Dynamic characteristics of litterfall and nutrient return of four typical forests along the altitudinal gradients in Mt. Shennongjia, China. Acta Ecol Sin 32:2142–2149

Lugo AE, Sanchez MJ, Brown S (1986) Land use and organic carbon content of some subtropical soils. Plant Soil 96:185–196

Podwojewski P, Poulenard J, Nguyet ML, De Rouw A, Nguyen VT, Pham QH, Tran DT (2011) Climate and vegetation determine soil organic matter status in an alpine inner-tropical soil catena in the Fan Si Pan Mountain, Vietnam. Catena 87:226–239

Porter WM, Robson AD, Abbott LK (1987) Field survey of the distribution of vesicular–arbuscular mycorrhizal fungi in relation to soil ph. J Appl Ecol 24:659–662

Preston CM (1996) Applications of NMR to soil organic matter analysis: history and prospects. Soil Sci 161:144–166

Quideau SA, Anderson MA, Graham RC, Chadwick OA, Trumbore SE (2000) Soil organic matter processes: characterization by ^{13}C NMR and ^{14}C measurements. For Ecol Manag 138:19–27

Rodeghiero M, Cescatti A (2005) Main determinants of forest soil respiration along an elevation/temperature gradient in the Italian Alps. Glob Change Bio 11:1024–1041

Rumpel C, Kögel-Knabner I, Bruhn F (2002) Vertical distribution, age, and chemical composition of organic carbon in two forest soils of different pedogenesis. Org Geochem 33:1131–1142

Schmidt M, Knicker H, Hatcher PG, Kögel-Knabner I (1997) Improvement of ^{13}C and ^{15}N CPMAS NMR spectra of bulk soils, particle size fractions and organic material by treatment with 10 % hydrofluoric acid. Eur J Soil Sci 48:319–328

Tewksbury CE, Van Miegroet H (2007) Soil organic carbon dynamics along a climatic gradient in a southern Appalachian spruce–fir forest. Can J For Res 37:1161–1172

Torn MS, Trumbore SE, Chadwick OA, Vitousek PM, Hendricks DM (1997) Mineral control of soil organic carbon storage and turnover. Nature 389:170–173

Trumbore SE, Chadwick OA, Amundson R (1996) Rapid exchange between soil carbon and atmospheric carbon dioxide driven by temperature change. Science 272:393–396

van Groenigen KJ, Six J, Hungate BA, de Graaff MA, van Breemen N, van Kessel C (2006) Element interactions limit soil carbon storage. Proc Natl Acad Sci USA 103:6571–6574

Vesterdal L, Schmidt IK, Callesen I, Nilsson LO, Gundersen P (2008) Carbon and nitrogen in forest floor and mineral soil under six common European tree species. For Ecol Manag 255:35–48

Wang S, Huang M, Shao X, Mickler RA, Li K, Ji J (2004) Vertical distribution of soil organic carbon in China. Environ Manag 33:S200–S209

Wang H, Liu SR, Mo JM, Wang JX, Makeschin F, Wolff M (2010) Soil organic carbon stock and chemical composition in four plantations of indigenous tree species in subtropical China. Ecol Res 25:1071–1079

Wang H, Liu S, Wang J, Shi Z, Lu L, Guo W, Jia H, Cai D (2013a) Dynamics and speciation of organic carbon during decomposition of leaf litter and fine roots in four subtropical plantations of China. For Ecol Manag 300:43–52

Wang H, Liu S, Wang J, Shi Z, Lu L, Zeng J, Ming A (2013b) Effects of tree species mixture on soil organic carbon and greenhouse gas fluxes in subtropical plantations in China. For Ecol Manag 300:4–13

Zech W, Haumaier L, Kögel-Knabner I (1989) Changes in aromaticity and carbon distribution of soil organic matter due to pedogenesis. Sci Total Environ 81–82:179–186

Zech W, Senesi N, Guggenberger G, Kaiser K, Lehmann J, Miano TM, Miltner A, Schroth G (1997) Factors controlling humification and mineralization of soil organic matter in the tropics. Geoderma 79:117–161

Zeng W, Tang S (2012) A new general biomass allometric model. Sci Sil Sin 48:48–52

Zimmermann M, Leifeld J, Conen F, Bird MI, Meir P (2012) Can composition and physical protection of soil organic matter explain soil respiration temperature sensitivity? Biogeochemistry 107:1–14